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Causes of Total Coliform-Positive Occurrences in Distribution Systems

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Background and Disclaimer

The USEPA is revising the Total Coliform Rule (TCR) and is considering new possible distribution system requirements as part of these revisions. As part of this process, the USEPA is publishing a series of issue papers to present available information on topics relevant to possible TCR revisions. This paper was developed as part of that effort.

The objective of the "white papers" is to review the available data, information and research regarding the potential public health risks associated with the distribution system issues, and where relevant, identify areas in which additional research may be warranted. The white papers will serve as background material for EPA, expert and stakeholder discussions. The papers only present available information and do not represent Agency policy. Some of the papers were prepared by parties outside of EPA; EPA does not endorse those papers, but is providing them for information and review.

Additional Information

The paper is available at the TCR web site at:

http://www.epa.gov/safewater/disinfection/tcr/regulation_revisions.html

Questions or comments regarding this paper may be directed to **TCR@epa.gov.**

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1. Overview

1.1 Purpose and Scope

As discussed in the paper "Total Coliform Rule and Distribution System Issue Papers Overview," EPA in 2003 announced its plans to assess the effectiveness of the current Total Coliform Rule (TCR) and to consider revisions to the TCR with new requirements for ensuring the integrity of the distribution system. Part of this assessment entails reviewing total coliform positive events and MCL violations to determine the extent of events that are captured by the existing TCR monitoring.

This paper on the causes of total coliform-positive occurrences in distribution systems reviews existing literature, research, and information on public water supply distribution system occurrences of total coliform bacteria and the circumstances and deficiencies identified as having caused those events. These occurrences include documented waterborne disease outbreaks where total coliform was detected; positive total coliform sample results; and acute violations of the Total Coliform Rule (TCR) (40 CFR Sections 141.21 and 141.63). This paper compiles causes of positive total coliform events, identifies commonalities between different events, and describes potential causes that may not have been reported in available event summaries for the purpose of highlighting potential strategies for control or prevention of the total coliform occurrence.

The scope of this paper includes appurtenances owned and operated by private customers (such as service lines), that are typically not considered the responsibility of the public water system purveyor since these appurtenances sometimes serve as a pathway to the distribution system or a source of contaminants. This paper does not provide a comprehensive listing of all documented total coliform occurrences or a statistical representation of the number or relative frequency of each cause of an event. Contamination events involving disinfectants, disinfection byproducts, lead, copper, and other chemicals found in the distribution system are only mentioned where total coliforms were also detected, or where the case study illustrates a pathway or mechanism important to total coliform occurrence. This paper does not address source water or water treatment deficiencies that result in a distribution system occurrence of total coliforms.

The majority of the contamination events described in this paper occurred in community water system distribution piping or finished water storage facilities. Community water systems typically have more extensive distribution piping, storage, and pressure complexities in comparison to non-community water systems. This distribution system complexity creates more opportunity for circumstances to create a contamination event. In addition, public health outcomes related to contamination events may more likely be detected in these types of systems since larger populations are potentially affected; consumer complaints are more likely from residential customers than transient populations; and residents are more apt to notice if something about their drinking water is abnormal. Several case studies from non-community water systems have been included for contamination events where the configuration of the distribution system is similar to a community water system (i.e., not just interior plumbing) and therefore the circumstances of the contamination could also occur in community systems.

1.2 Definitions

Causes are the specific failure mechanisms, pathways, and sources of contaminants that contribute to the occurrence of total coliforms.

Community water system is a public water system which serves at least 15 service connections used by year-round residents or regularly serve at least 25 year-round residents (40 CFR Section 141.2).

Contamination event is defined as the combination of circumstances that allows an undesirable microbial (e.g. coliforms) and/or chemical substances in the distribution system. Contamination occurs when a source of contaminants is present (e.g., untreated sewage in soil external to pipeline), a pathway to the distribution system exists (e.g., open pipeline for repair, point of leakage, or faulty seal), and a mechanism that allows the contaminant to travel through the pathway to the distribution system (e.g., pressure conditions). Contamination events can be chronic, intermittent or short-term occurrences. They are not restricted to documented waterborne disease outbreaks or violations of National Primary Drinking Water Regulations (NPDWRs).

Distribution system is defined as a system of conveyances that distributes potable water including all pipes, storage tanks, pipe laterals, and appurtenances that comprise the delivery system.

Non-community water system is a public water system that is not a community water system. A non-community water system is either a transient non-community water system or non-transient non-community water system (40 CFR Section 141.2).

Pathway is an entry point to the distribution system or mechanism that allows contaminants to enter the distribution system. Examples include physical openings in the pipes or storage facilities such as faulty seals, leakage points, unprotected vents or pipe openings for repairs.

Public water system (PWS) is a system for the provision to the public of water for human consumption through pipes or, after August 5, 1998, other constructed conveyances, if such system has at least 15 service connections or regularly serves an average of at least 25 individuals daily at least 60 days out of the year (40 CFR Section 141.2).

Waterborne disease outbreak is the occurrence of two or more individuals experiencing a similar illness after exposure to water and epidemiological evidence implicates water as the probable source of illness. If water quality data indicate chemical contamination or laboratory-confirmed primary amebic meningoencephalitis, a single case of illness is considered a waterborne disease outbreak. Outbreaks that are attributed to the contamination of drinking water at its point of use (e.g., a contaminated water faucet or serving container) are not classified as waterborne disease outbreaks by the CDC (Lee et al., 2002).

2. Information Sources

Sources used to obtain information on total coliform occurrences within the distribution system are discussed in Section 2.1. Data from waterborne disease outbreak reports are discussed in Section 2.2. Information regarding total coliform-positive events is detailed in Section 2.3.

2.1 Contamination Events and Data from the United States and Other Developed Countries

Research reports published in peer-reviewed journals and other literature specifically addressing distribution system water quality provide actual and potential contamination scenarios. Anecdotal reports from newspapers and e-based periodicals were used where the cause of a contamination event was clearly established as having been distribution system-related. EPA regional offices were also contacted to verify information on events and to describe additional events, where possible.

Additional data sources include the following:

- Safe Drinking Water Information System (SDWIS). The SDWIS database was queried for events that indicated bacterial contamination to verify if TCR violations coincided with the event (described in more detail in Section 2.3).
- Consumer Confidence Reports (CCR) database. CCRs were obtained, where available, to further expand on events and verify causes.
- Surveys. Surveys conducted by national organizations, such as American Water Works Association (AWWA), were investigated to obtain statistics on industry practices that may highlight causes of events.
- National Oceanic and Atmospheric Administration (NOAA). The NOAA database was queried to determine if significant weather during or near an event may have contributed to the contamination event. Correlations were found with catastrophic events but a thorough analysis of more typical events was not completed.

2.2 Waterborne Disease Outbreak Reports

Contamination events that result in illnesses may be recognized by local public health officials or others, and in some instances, reported to the Centers for Disease Control and Prevention (CDC). CDC's investigation will determine if the contamination event meets the criteria of a waterborne disease outbreak, and therefore will be included on the CDC report.

Since 1971, EPA, the CDC, and the Council of State and Territorial Epidemiologists have maintained a collaborative surveillance system for collecting and reporting data on the occurrences and causes of waterborne disease outbreaks in community and non-community public water systems. Where CDC has determined a waterborne disease outbreak has occurred, details on the cause(s) of the waterborne disease outbreak are often recorded and made publicly available by CDC. The investigative work for these types of outbreaks is focused on determining the circumstances leading to the outbreak.

The primary responsibility for detecting and investigating waterborne disease outbreaks falls with state, territorial, and local public health agencies. The results of the investigations are voluntarily reported to CDC on a standard form. The form is used to record the following:

- Data related to characteristics of the outbreak.
- Results from epidemiological studies.
- Specimen and water sample testing.
- Factors contributing to the outbreak, including environmental factors, water distribution, and disinfection concerns.

CDC obtains additional needed information from the state's drinking water agency, which are analyzed and included in their disease outbreak reports and summaries.

Craun and Calderon (2001) analyzed the causes of waterborne disease outbreaks associated with chemical and microbial contaminants entering the distribution system or storage facilities, and water that was corrosive to plumbing systems within buildings or homes for the period 1971 to 1998. CDC reports (Lee et al., 2002; Blackburn et al., 2004) provide additional information on outbreaks that occurred from 1999 through 2002, as well as outbreaks previously unreported in 1995 and 1997. Among these summaries, data are provided for distribution system-related outbreaks from 1971 to 2002. The data show outbreaks occurred in both community and non-community public water systems. In this time period, 126 of 689 (approximately 18 percent) of the reported waterborne disease outbreaks were caused by distribution system deficiencies.

Exhibit 1 summarizes the findings regarding outbreaks in community and non-community water systems caused by distribution system deficiencies from 1971 through 2000. Specific examples of some of these outbreaks are also included later in this paper under the discussion of contaminant pathways and causes of contamination events.

2.3 Total Coliform-Positive Events

SDWIS database and information provided by EPA regional offices were used to determine if coliform-positive events or TCR violations coincided with microbial contamination events presented in this paper. According to the USEPA, more than 9,000 TCR maximum contaminant level (MCL) violations occurred each year from 2000 through 2004 (http://www.epa.gov/safewater/data/getdata.html).

An association between waterborne disease outbreaks and coliform-positive events was studied by Craun et al. (1997). This study reviewed epidemiologic investigative reports of waterborne disease outbreaks and available coliform data. The evaluation included waterborne disease outbreaks reported during 1983-1992. The authors found that water samples from 52 percent of the community water systems and 87 percent of the non-community water systems showed the presence of coliform organisms during the outbreaks. In community systems,

Exhibit 1. Distribution System Deficiencies Causing Outbreaks in Community and Non-community Water Systems 1971-2000

Deficiency Causing Distribution System-Related Outbreaks	Number of Distribution System-Related Outbreaks			Percentage of Distribution-Related Outbreaks by Deficiency
	CWS*	NCWS**	Total	
Cross-connection/backsiphonage	49	15	64	53.3
Corrosion/leaching of metals	12	1	13	10.8
Broken or leaking water mains	11	0	11	9.2
Contamination during storage	9	6	15	12.5
Contamination of mains during construction/repair	5	1	6	5.0
Contamination of household plumbing	9	1	10	8.3
Inadequate separation of water main and sewer	1	0	1	0.8
Total	96	24	120	

* Community water system
**Non-community water system
Sources of data: Craun and Calderon (2001); Lee et al. (2002).

coliforms were detected in 63 percent of the outbreaks attributed to distribution system deficiencies or unidentified deficiencies. The authors noted increased sampling for coliform organisms, above that required for compliance monitoring, may have occurred during the outbreaks. Coliform-positive water samples were also reported in the several months before an outbreak in 26 (54 percent) of 48 public water systems with available information, but data were limited and the authors could not rule out the influence of random error.

Where available, information is provided on coliform sampling and TCR violations for case studies presented in Section 4.

3. Data Limitations

Certain causes of events are identified more frequently due to the magnitude of their impact (e.g., on a large number of people), the ease by which they are recognized by consumers and trigger a response (e.g., taste, odor, or appearance of the water), and/or the conditions under which they occur (e.g., large scale impact for long term). For an event to be detected through distribution system monitoring, the monitoring program must include the affected area of the system at the same time and location that the indicator or contaminant are detectable. Subsequent investigation of the cause of such an event may be delayed by the time required for sample analysis, and the circumstances resulting in the initial event may no longer be detectable.

Data on the causes of distribution system contamination events are limited for several reasons:

- Limitations in distribution system monitoring and data interpretation.
- Limitations with correlating illness to distribution system occurrences.
- Difficulty with reporting and archiving contamination events.

The effect these limitations have on the availability of historical contamination events data, and the uncertainty inherent in reported data, is further described below.

3.1 Distribution System Monitoring and Data Interpretation

Most distribution system monitoring for coliform bacteria involves taking samples at specific times and locations within the distribution system. These samples reflect water quality at discrete points and times, not on a continuous or universal basis. Craun and Calderon noted that analysis of water quality data collected during outbreaks indicated most reported distribution system outbreaks were caused by significant or continuing contamination (Craun and Calderon, 2001). Contamination events that are of a larger magnitude and longer duration are more likely to be detected than short-term or intermittent events, such as many distribution system contamination events. Furthermore, the TCR requires monitoring at points that are "representative" of the distribution system. Many different interpretations of what is considered "representative" exist, which results in varying criteria specified by different States. This presents challenges to the interpretation of the monitoring information on a national basis.

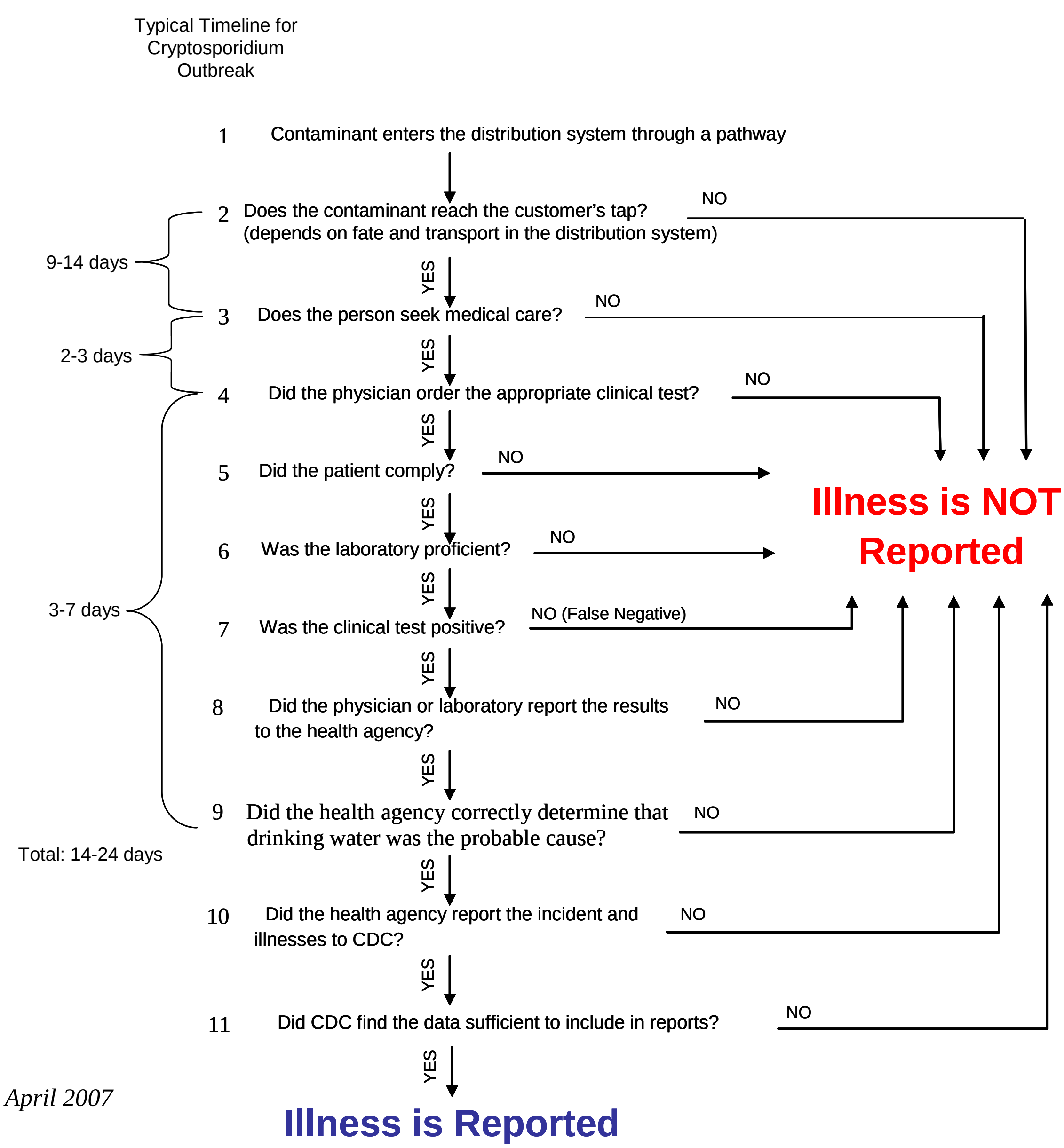
One factor affecting a water system's ability to identify a distribution system contamination event are the limitations associated with the use of total coliforms as indicators of fecal contamination to a water distribution system. While the presence of total coliform bacteria in a water sample may be the direct result of fecal contamination, total coliforms can also originate from environmental sources (e.g., soil) or from biofilms. Many of these environmental total coliform species are not known to pose a threat to public health. Total coliforms can also be present due to a number of contamination pathways such as treatment breakthrough, cross-connections, and intrusion (Craun and Calderon, 2001). These pathways can introduce fecal pathogens to the distribution system.

High levels of heterotrophic bacteria can interfere with total coliform analysis in lactose-based culture methods such as membrane filter (Geldreich et al., 1972). Experimental studies have also shown that HPC bacteria will out-compete coliform organisms for low levels of nutrients (LeChevallier and McFeters, 1985).

3.2 Correlating Illness to Distribution System Total Coliform Positive Events

Another issue in identifying contamination events is limitations associated with correlating an illness to the distribution system. Even if many illnesses result from contamination events, it is difficult to establish a link between the illnesses and the event because a very small volume of the distributed water is sampled, and the system would have to monitor in the right place at the right time. In addition, it is difficult to attribute symptoms of illness to drinking water contamination. Many other barriers exist in attributing illness to drinking water, such as the customers not seeking health care and lack of physician reporting results to the health agency. Unless a confirmed case of illness triggers a report to health agencies (with subsequent investigative follow-up by the health agencies and the water utility), an incident of contamination may not be identified. The time interval required for ingestion, development of symptoms, medical diagnosis and treatment, and investigation of the source of the disease may be weeks or months. For instance, it can take 14 to 24 days between ingestion and reporting of an outbreak associated with *Cryptosporidium* (see Exhibit 3). By the time a water sample is collected, days or weeks may have lapsed and the contaminant may no longer be present. If contamination of the distribution system was temporary or intermittent, subsequent investigative sampling may not identify any contamination or recover the causative agent of disease. In addition, the illness may be thought to be caused by another source, such as foodborne contamination or by person-to-person contact. Exhibit 3 presents the numerous steps that typically occur before a waterborne disease outbreak is recognized.

Exhibit 3. Chronology of Illness Reporting (Adapted from Frost et al., 1996) and Typical Timeline for Cryptosporidium Outbreak and Reporting (Juranek, 1997)



Four full-scale epidemiology studies (household intervention studies) designed to measure endemic waterborne illness demonstrate the difficulties with identifying cases of illness associated with drinking water and/or distribution system contamination. These studies were conducted in communities served by surface water systems in the United States, Canada, and Australia (Payment et al., 1991; Payment et al., 1997; Hellard et al., 2001; Colford et al., 2002). Each of the household intervention studies measured differences in the incidence of gastroenteritis symptoms (e.g., diarrhea, vomiting) reported by persons in participating households that had been randomly assigned to one of a number of different household drinking water interventions (e.g., point-of-use treatment of tap water) or to the "no treatment" option (regular tap water, or a placebo treatment device in the case of a blinded study).

Two studies were unable to detect illness attributable to drinking water (Colford et al., 2002; Hellard et al., 2001). Neither of these studies was designed specifically to differentiate between illness caused by contamination resulting from inadequacy of water treatment before entry to the distribution system and contamination originating in the distribution system.

The two studies by Payment et al. (1991 and 1997) indicate gastrointestinal illnesses due to consumption of tap water may be more common-place than typically recognized. The first study by Payment et al. (1991) compared the illness patterns among 300 households that drank from reverse osmosis (RO) point-of-use treatment devices installed at the kitchen tap and 300 households that drank normal tap water. This study was conducted for a 15-month period and reported a 35 percent lower rate of gastrointestinal illness in the group that drank RO filtered water than in the group that drank tap water. The rate of gastrointestinal illness was also compared by zones in the distribution system. People living at the end of the distribution system had rates of illness twice as high as people living near the treatment plant or close to the rechlorination sub-station. The authors concluded that the observed excess illness was not epidemic in nature because the illnesses were distributed throughout the year and not clustered in specific areas at specific times. They also concluded that sporadic problems at the treatment plant were not the source of the effect because the excess risk increased, rather than decreased, with distance from the plant. There was no correlation observed between the incidence of gastrointestinal symptoms and total or fecal coliforms.

The study by Payment et al. (1997) was conducted in the same community following major treatment improvements at the treatment plant and higher disinfectant residual entering the distribution system. The study was comprised of 1400 families who were divided into four groups. One group drank tap water, one group drank tap water from a continuously purged tap, one group drank bottled water taken from the treatment plant, and another group drank purified bottled water (spring water or water treated with RO). It was theorized that the water from the continuously purged tap would be representative of water in the distribution system. The group drinking purified bottled water was used as a baseline for comparison. Participants were asked to keep health diaries and complete questionnaires related to their health and water consumption for the duration of the study (up to 16 months).

The results of the study showed that among participants drinking regular tap water, 14 percent of gastrointestinal illnesses were attributable to consumption of the tap water. Among individuals drinking water from the continuously purged tap, 19 percent of gastrointestinal illnesses were attributable to drinking that water. Incidence rates among children 2 to 5 years old were higher (up to 40 percent). There was no significant difference in the incidence of gastrointestinal illness between participants who drank bottled plant water and those that drank bottled purified water. The significantly higher incidence of illness among participants of both groups assigned to drinking tap water (compared to the incidence among those assigned to drinking bottled water) suggests that the distribution system might be the main source of the observed difference; however, the authors concluded that it was not possible to conclusively establish the contribution of the distribution system and household plumbing to the observed higher incidence of illness. The fact that the bottled treated plant water was only collected at the plant during periods of optimal filtration means the study did not measure the incidence of drinking water attributable illness during periods when it would have been more prevalent, thereby underestimating the rate of illness due to treatment deficiencies and overestimating the risk due to distribution system problems. Also contributing to the higher incidence rate among those assigned to continuously purged tap group could be higher levels of pathogens in the distribution system surviving disinfection because of the shorter disinfectant contact time. The authors conclude that the high rate of illness among participants of the continuously purged tap group pointed to the distribution system as a major source of the unknown etiologic agents responsible for the reported illnesses.

The results of the two household intervention studies by Payment et al. (1991 and 1997) suggest that distribution system contamination may be responsible for a substantial fraction of endemic waterborne illness, but the authors were not able to quantify the fraction.

3.3 Reporting and Archiving Total Coliform Positive Events

Reporting of waterborne illnesses to CDC is currently voluntary. It is estimated as few as 10 to 30 percent of waterborne disease outbreaks in the United States are reported (Craun and Calderon, 2001). This under-reporting of waterborne disease outbreaks does not include those waterborne illnesses that fail to meet the definition of an outbreak, such as endemic illnesses or waterborne illnesses where an association with water was not established. Therefore, contamination events within the distribution system may be significantly higher than those reported and documented. Because the majority of contamination episodes are not reported or documented, it is difficult to derive a statistically accurate representation of the different types of contamination events and associated causes.

In addition, there is no existing national database or central archive for reporting or storing distribution system contamination events. These two factors further limit the availability of information on distribution system contamination events data.

4. Possible Causes of Total Coliform Occurrence

Similar to other contamination events, the occurrence of total coliform bacteria in the distribution system requires three factors to be present: a source of total coliform bacteria; a pathway into the distribution system or a breach in the system's physical integrity; and a mechanism that allows the bacteria to be carried on this pathway into the distribution system. For example, a cross connection is a pathway whereby a piping connection exists between a private water system and the public water system. Backflow through this cross connection is the mechanism that allows untreated water containing the bacteria to enter the water distribution system. As stated in Section 1.1, this paper does not address water treatment breakthrough as a mechanism for total coliform occurrence. The paper also does not include total coliform occurrence from untreated source waters. Although there are often multiple causes to total coliform positive events, in the following sections, case study examples are organized according to their primary cause.

4.1 Sources of Total Coliform Bacteria

Reported sources of total coliform bacteria in the distribution system include the following:

- Soil and Water Surrounding Pipes
- Biofilms and Microbial Growth
- Corrosion Tubercles
- Weather-Related Events
- Customer Connections
- Materials Added to the Distribution System
- Sediments

4.1.1 Soil and Water Surrounding Pipes

A list of potential sources of microbiological contamination at water main repair sites was compiled by Pierson et al. (2001). Prior to the repair, contaminant sources may include soil/sediment; animal or human waste; dead animals; unsanitary human contact; incidental dirty water; or trash. During the repair, contaminant sources may include soil/sediment; animal wastes; unsanitary human contact; groundwater or sewage in the repair trench; or agricultural runoff in trench.

Besner et al. (2005) studied the occurrence of microbial intrusion into distribution systems by collecting and analyzing soil and water samples at water main repair sites, customer houses and adjacent hydrants. For example, at one repair site, microbiological analyses conducted on soil and water samples detected aerobic spore formers, actinomycetes, total coliforms, and *Clostridium perfringens*, an indicator of fecal contamination. After the repair was complete, the water main was flushed from a nearby hydrant. Microbiological analyses of the flushed water detected aerobic spore forming bacteria, *E. coli*, total coliforms, and actinomycetes. This repair site was the only one of 14 repair sites where *E. coli* was detected in the flushed water. No positive samples were collected from customer houses after flushing was complete.

Besner et al. (2004) also studied possible sources of microbiological contamination at water main repair sites. Of nine soil samples and six water samples collected from the immediate vicinity of excavated mains, *E. coli* was detected in one soil sample but the water sample from that repair site was too dirty to allow analysis. *Clostridium perfringens* was detected in two of the six water samples and three of the nine soil samples.

Kirmeyer et al. (2001) conducted microbial analyses of soil and water samples at water main repair sites and found evidence of fecal pollution. Total coliforms were detected in 58 percent of water samples and 70 percent of soil samples. Fecal coliforms were detected in 43 percent of water samples and 50 percent of soil samples. A total of 65 samples were collected (32 water samples and 33 soil samples) from eight utilities in six states.

When pipes are stored at the construction site without protective caps, they are easily contaminated with dirt, mud, debris, and dirty water. These conditions may lead to water quality problems such as high turbidity, high heterotrophic bacteria counts, and coliform bacteria occurrence (Korntreger and O'Donnell 1998). As reported by Haas et al. (1998),

> "Clark et al. (1982) used coliform tests to evaluate new mains for bacterial contamination. They found that new mains contained species of *Enterobacter*, *Klebsiella*, *Escherichia*, and *Citrobacter* as well as *Aeromonas hydrophila*, an opportunistic pathogen…*Citrobacter freundii* is commonly found in soil and suggests the soil contamination of new mains."

Besner et al. (2005) also identified a possible source of bacteria during a main repair when a replacement valve was placed onto fecally-contaminated soil and installed without proper disinfection.

As reported in Haas et al. (1998), Harris (1959) investigated the bacterial loading of trenches and found the largest bacterial densities in trench bottoms next to existing pipe.

> "Moisture content increased bacterial counts substantially (up to 100-fold). Thus, damp soil near a leaking main is a potential source of massive bacterial contamination during repairs. (Haas et al. 1998)"

In Cabool, Missouri, from 1989-1990, *E. coli* O157: H7 were introduced at or near the sites of two large water main breaks and numerous service meter breaks. The water main and service meter breaks were attributed to extremely cold weather. Sewage overflow from manholes of a nearby deteriorating sewer collection system during heavy rains was thought to be the source of contamination (Geldreich et al., 1992).

4.1.2 Biofilms and Microbial Growth

Biofilms are defined as a complex mixture of microbes, organic, and inorganic material accumulated amidst a microbially-produced organic polymer matrix attached to the inner surface of the distribution system (USEPA, 2002). Contaminants, including total coliforms and some pathogens, may attach to or become enmeshed in biofilms on pipe walls in distribution systems. Many pathogens have been found to survive and sometimes increase in number in these pipe biofilms where they are protected from disinfectants. Over time, these pathogens may detach or slough from biofilms, causing persistent detections and even waterborne disease. Biofilm can result in total coliform-positive and other contamination events if disturbed, such as during a sudden change in flow. More detailed background information is provided in the USEPA (2002) white paper including the potential public health risks of biofilms, characteristics of specific microbes, and factors that influence pathogen survival and growth. The following case study gives a specific example of coliform occurrence linked to biofilms.

Biofilms on gate valves with rubber-coated wedges were identified as a cause of coliform contamination of drinking water without disinfectant residual (Bendinger et al., 2004). Coliforms were detected in water samples 12 months after new piping was installed. Nine gate valves were removed from this piping and examined. On visual inspection, all rubber-coated wedges were covered by excessive biofilms. Bacterial testing found coliform bacteria on all rubber surfaces but no *E. coli*. Since coliforms of the same species were found in the drinking water and the rubber surfaces, it was assumed that the coliform bacteria entered the drinking water from the biofilm.

4.1.3 Corrosion Tubercles

Friedman et al. (2003) summarized technical literature documenting cases of coliform bacteria present within corrosion tubercles. LeChevallier et al. (1987) identified *E. coli* within tubercles collected from bituminous-coated, cement-lined cast iron pipe. Emde et al. (1992) found that total coliforms were present in greater numbers in corrosion deposits than in the untreated water supply. The authors examined corrosion tubercles from exhumed pipes and found 22 types of bacteria, including *E. coli* and *Klebsiella spp.*

4.1.4 Weather-Related Events

A range of different weather-related events can contribute to the occurrence of total coliforms, and sometimes fecal indicators, in drinking water distribution systems. In some cases, the indicators may increase in the source waters, while in other cases they may enter the distribution system more directly. The types of weather-related events that have been contributed to indicator positive samples include significant rainfall events, droughts, and excessively warm or cold weather. Significant rainfall was suggested as a possible cause of total coliform positive samples in Bristol, Connecticut in 2005 (The Bristol Press, 2005), and Yamhill County, Oregon in 2006 (Oregon Department of Health Services, 2006). Snowmelt was suggested as a possible cause of total coliform positive samples in East Providence, Rhode Island in 2003 (East Bay Newspapers, 2003) and in White Lake Township, Michigan in 2005 (The Daily Oakland Press, 2005), as well as the possible cause of *E. coli* occurrence in Lisbon, New Hampshire in 2005 (Littleton Courier, 2005). High temperatures may have also contributed to total coliform positive samples in Rockdale County Georgia in 2003 (Gwinnett Daily Post, 2003).

4.1.5 Customer Connections

Customer connections can be the source of total coliform bacteria when a backflow event has occurred. In Norridgewock, Maine in 1991 backsiphonage from a failure of a restaurant's septic system led to the presence of total and fecal coliforms (EPA Region 1, 1991). Coliform bacteria were also detected in samples in Goodyear, Arizona in 1988. The suspected cause was backflow contamination from a construction site (EPA Region 9, 1988). In April

1991 in San Antonio, Texas, total coliform bacteria entered the distribution system from a heating and cooling system in an Air Force base (EPA Region 9, 1991).

4.1.6 Materials Added to the Distribution System

In some instances materials added to the distribution system can result in the presence of total coliforms. These can result from the materials themselves being contaminated, and from materials that can support the growth of coliforms by providing nutrients for microbial growth. *E. coli* contamination was detected in the Woodburn, Oregon drinking water supply in 2005. Contamination due to construction activity was mentioned as one possible cause (Statesman Journal, 2005). Similarly, construction activity was mentioned as a possible cause of total coliform contamination of the Lacey, Washington distribution system in 2004 (The Olympian, 2004). Some construction materials, such as rubber, silicon, polyvinyl chloride, and bituminous coatings can stimulate microbial growth (USEPA, 1992).

4.1.7 Sediments

Sediment accumulation can provide a habitat for microbial growth in a distribution system (USEPA, 1992). Furthermore, the sediments can provide the microbes protection from disinfectants. Besner et al. (2001) identified sediment accumulation in a low-flow main as a possible source of total coliforms in a sampling point on “B Street” in the Montreal distribution system.

4.2 Pathways for Total Coliform Bacteria to Enter Distribution Systems

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This section focuses on the pathways that allow contaminants to enter the distribution system from the sources described in Section 4.1. According to the National Academy of Sciences report *Drinking Water Distribution Systems: Assessing and Reducing Risks*, physical integrity determines: “…the ability of the distribution system to act as a physical barrier that prevents external contamination from affecting the quality of the internal, drinking water supply.” (National Research Council, 2006). Total coliforms and pathogens can be introduced to the distribution system through a variety of pathways, including:

- Finished Water Storage Facilities
- Cross Connections and Backflow
- Intrusion and Main Breaks
- Treatment Breakthrough

Kirmeyer et al., 2001 also held an expert panel workshop to prioritize the pathogen routes of entry into distribution systems that had been identified in a literature review. High priority pathways included cross connections, water main repair sites, and transitory contamination due to pressure transients. Uncovered storage facilities were classified as a medium priority pathway. Covered storage facilities and bacteria growth/resuspension were considered low priority pathways.

These pathways are described in more detail in the following section using case study examples. Further background information can be found in the distribution system white papers (http://www.epa.gov/safewater/disinfection/tcr/regulation_revisions.html).

4.2.1 Finished Water Storage Facilities

Storage tank deficiencies, such as vents without screens, inadequate hatches, access hatches that are not locked, physical openings in storage tank roofs, and lack of a cover, can result in the entry of contaminants. Microorganisms can also be introduced into ground storage facilities from surface water or groundwater infiltration or runoff.

> "Although they may suffer from structural failures, storage facilities are most susceptible to external contamination due to the absence or failure of an essential component, such as a cover, vent, hatch, etc. The complete absence of a cover or vent on a storage facility can allow birds access to the tank and subsequently introduce microbial pathogens such as bacteria…" (National Research Council 2006)"

A finished water storage facility was identified as the pathway for *Salmonella typhimurium* that caused a community outbreak of salmonellosis in Gideon, Missouri, in 1993 (Clark et al., 1994). It was estimated that the outbreak caused 650 people to become ill and caused seven deaths. The system's covered storage tanks were not properly maintained and holes in the roof of one tank allowed bird droppings and feathers to enter. Pigeons were found roosting on the tanks. *S. typhimurium* was detected in the sediment from one of the storage tanks. The sediment was upset when the water in the storage tank became unstratified due to temperature changes. Subsequent flushing performed in response to taste and odor complaints carried the sediment throughout the distribution system. The system did not have full-time chlorination when the outbreak occurred, but installed full-time chlorination shortly after the outbreak. Routine TCR monitoring did not indicate a problem, but water samples collected after the system became aware of the outbreak were positive for fecal coliforms.

From January 1991 through May 1994, the Missouri Department of Natural Resources (MDNR) found that 18 of 51 (35 percent) boil water orders in water systems with elevated tanks were due to contamination of the tanks. Deficiencies noted included defects in the hatch, vent, overflow, and in the joint between the wall and roof overhang, and holes that tank painting contractors did not repair subsequent to hanging internal rigging (Atkinson, 1995). Birds and related debris were identified as the contaminants. The boil water orders were triggered by detection of fecal coliform-positive water samples and acute MCL violations. The MDNR was also aware of an additional 15 situations where an acute MCL violation did not occur despite subsequent discovery of contamination in the tanks. MDNR theorized that full-time disinfection of the water supplies might have masked the presence of fecal coliforms in the contaminated tanks.

An acute TCR violation caused by *E. coli* contamination of the Point Evans, Washington water system in November 2003 was attributed to a storage tank. A system inspection showed no signs of vandalism or unauthorized entry, but heavy rains may have caused water that normally runs safely off the roof of one tank to seep into a second tank near an overflow vent, according to a water company bulletin (Sherman, 2004). The hatch was found to have a deficient seal, possibly serving as an entry point for contaminants. The system did not practice full-time disinfection at the time of this event (Ryding, 2004). The Washington Department of Health issued a boil order.

In 1995, a water district in Maine traced a total coliform bacteria occurrence in the distribution system to two old steel tanks with wooden roofs (Hunt, 2002). Inspection of the tanks revealed missing roof shingles and large gaps in the tank roofs were present. The tanks were drained and an interior inspection found two feet of accumulated sediment, widespread coating failure on the tank sidewalls, and evidence of human entry. The tanks were cleaned and the distribution system was flushed and disinfected. A boil water order was in place until system water quality was restored.

Finished water reservoirs with floating covers may become contaminated if the cover is damaged; allowing accumulated untreated water on the cover to mix with the finished water. At Philadelphia's Oak Lane Reservoir, surface water collected on the floating cover was found to contain fecal coliform bacteria counts as high as 13,000 per mL (Kirmeyer et al., 1999).

Although the City of Woodburn, Oregon could not definitively determine the cause of the *E. coli* found in one sample at the new Parr Road reservoir in May 2005, several small holes were found around seals and wire entry points on the reservoir's cathodic protection system and the reservoir exhaust system (http://www.ci.woodburn.or.us/publicworks/water/CCR%20-%202005%20-Eng.pdf). On the same day, a sample from the country club reservoir tested positive for total coliform bacteria. Further testing resulted in three positive total coliform samples which triggered a boil-water advisory.

A city in Massachusetts detected fecal coliform bacteria in several samples at one of their six finished water storage facilities (Correia, 2002). The tank inspector discovered an open access hatch and other signs of vandalism on one of the tanks. This tank was drained and cleaned to remove several inches of accumulated sediment. Three other finished water storage facilities were cleaned in 2001 without being drained and removed from service. The tank closest to the filtration plant was found to contain two to three inches of sediment and the tanks in outlying areas contained four to six inches of sediment. Shortly after the tanks were cleaned, the city experienced widespread total coliform occurrences in the distribution system. The city's immediate response was to boost the free chlorine residual in the distribution system and tank outlets to 4.0 mg/L. Also, the distribution system was flushed continuously for two days to remove contaminated water. These measures resolved the coliform bacteria problem. A boil order was not required. (Friedman et al., 2002b.)

4.2.2 Cross Connections

A cross connection can be defined as "any unprotected actual or potential connection or structural arrangement between a public or private potable water system, and any other source or system through which it is possible to introduce into any part of the potable water system any used water, industrial fluids, gas, or substance other than the intended potable water with which

the potable system is supplied" (USC-FCCCHR, 1993). Some common examples of cross connections include potable water system connections to industrial or commercial processes, carbon dioxide beverage dispensers, a leaking hydrant foot valve, garden hose sprayers, cooling systems, irrigation systems and fire sprinkler systems.
The EPA Distribution System White Paper (http://www.epa.gov/safewater/tcr/pdf/ccrwhite.pdf) provides additional background information on cross connections and possible health impacts. Two case studies that link total coliform or *E. coli* occurrence to a cross connection are summarized below.

A cross connection was determined to be the probable cause of an *E. coli* outbreak in August, 2000, at a county fair in Ohio (Lee et al., 2002). Twenty-nine persons who had attended the county fair had confirmed cases of *E. coli*. Consumption of food and beverages purchased from vendors within a particular area of the fairgrounds was found to be a substantial risk factor. An investigation found a cross-connection between the branch of the water distribution system supplying those vendors and an animal show barn. Spigots connecting hoses to both the animal areas and the concession stands did not have backflow prevention devices. Backsiphonage from the hoses in the animal areas was determined to be the probable cause of the outbreak.

In June 2001, an employee of the Mauriceville Special Utility District in Texas incorrectly assumed that a discolored water line was a sewer line and connected a sewer line to it (U.S. Water News Online, 2001). As a result, sewage contaminated the drinking water supply for about 20 days before customer complaints about particles in the water prompted the utility district to conduct sampling. The samples came back positive for fecal coliform bacteria and resulted in an acute TCR violation. About 2,000 customers were affected by the contamination and had to boil their drinking water or use bottled water.

4.2.3 Intrusion and Main Breaks

Intrusions through leaks, as well as main breaks, can provide a pathway for contaminants outside of the pipe to enter the distribution system during low and negative pressure events. Points through which intrusions can occur also include pipeline fracture cracks, leaking joints, leaking adapters and deteriorating seals (Kirmeyer et al., 2001).

On March 28, 2004, a boil-water advisory was issued for residents of a seven-block section of Pacific, Missouri after a water distribution system sample tested positive for coliform bacteria, resulting in a TCR violation (Masson 2004). The sample tested negative for *E. coli*. The contamination was suspected to be related to a recent water main break. Another sample taken three days earlier had tested negative for bacteria, but was reported to have an odd smell. This prompted water system personnel to test additional samples from that area, including the sample in which the unknown bacteria were found. As a precaution, the water system crews also opened three fire hydrants to flush the affected area of the distribution system.

Besner et al. (2001) identified that the source of total coliform bacteria for a sampling point on "B Street" in the Montreal distribution system was likely due to a series of water main breaks on a nearby 14-inch main. The authors also showed that flow reversals in summer months could bring water containing low chlorine residual past this 14-inch main toward the sampling point.

In the Cabool, Missouri outbreak, Swerdlow et al. hypothesized a “pocket” of contamination may have been able to enter the distribution system during main and service meter breaks or on a long-term, minor flow rate basis (through seepage into the system) (Swerdlow et al., 1992, Craun et al., 2001). Hyperchlorination was not part of the main repair process or of meter replacements. The water system also did not use full-time disinfection. Routine coliform monitoring did not indicate a problem and the water system did not have any coliform violations during this time period. This outbreak resulted in four deaths, 32 hospitalizations, and a total of 243 documented cases of diarrhea.

4.2.4 Treatment Breakthrough

One current objective of total coliform monitoring is to indicate the effectiveness of treatment. Therefore, total coliforms have broken through the treatment barriers; they may be detected in samples collected in the distribution system. Failure of the treatment barrier was noted in Aurora, Illinois when elevated levels of ammonia decreased the ability of chlorine to disinfect. *E. coli* was detected in the distribution system (City of Aurora, 2004). Mechanical problems at a water treatment plant led a water plant in Bandon, Oregon to distribute water potentially containing fecal coliforms and *E. coli* from the source water in 2005 (theWorldlink.com, 2006). Low chlorine levels were a possible contributor to the detection of *E. coli* in Warren County, Mississippi in 2007 (Vicksburg Post, 2007). In addition, even in systems that provide treatment and are in compliance, the distributed water is not sterile. As such, some total coliforms have the potential to enter the distribution system, even in well-treated systems.

4.3 Mechanisms that Allow Total Coliform Bacteria to Enter or Proliferate in Distribution Systems

This section addresses the driving forces that may allow for total coliforms or fecal indicators to enter or proliferate in a distribution system if a source of contaminants and/or a pathway exist. The mechanisms discussed in the paper are:

- Hydraulic Conditions
- Operations
- Maintenance Practices
- Retention Times
- Presence of Nutrients

4.3.1 Hydraulic Conditions

The operating pressure in a water distribution system fluctuates over time and location, depending on several factors such as pipe elevation, operating setpoints for booster pumps and system valves, storage tank water levels, and water demand variations. Pressure losses can occur in the distribution system as a result of certain events including flushing, main breaks, power outages, service line breaks, and fire events (ABPA 2000). Pressure transients (also called pressure surges or water hammer) can occur when an abrupt change in water velocity occurs, due to a sudden valve closure, pump shutdown, or loss of power (Friedman et al. 2004). The resulting pressure wave, with alternating low and high pressures, travels back and forth through the distribution system until the pressure is stabilized.

LeChevallier et al. (2002) and Friedman et al. (2004) have documented occurrences of low and negative pressures within distribution systems during transient pressure events. Many of the causes of pressure transients are a part of regular water distribution system operations and therefore, pressure transients may occur frequently in certain water distribution systems, as demonstrated by Friedman et al. (2004). Further information on pressure transients are discussed in the Distribution System White Paper (http://www.epa.gov/safewater/tcr/pdf/intrusion.pdf).

Besner et al. (2002) summarized an investigation by McMath and Casey (2000) who measured subatmospheric pressures at one distribution system point during surges. This point was an air valve chamber that flooded with dirty water during wet weather. The authors identified intrusion of dirty water through the air valve chamber during low pressure conditions as a possible cause of the high coliform detection rate in distribution system water samples collected near this point.

Contaminant intrusion may occur if a very low or negative pressure occurs within the pipe at a leakage point or other gap in the piping system where the external pressure is higher (LeChevallier et al., 2002). One example of high water pressure external to the pipe is a high ground water table. A source of contaminants in the soil and water outside the pipe must also be present to allow contaminant intrusion to occur.

Low pressure conditions in the distribution system can allow a flow reversal or backflow of non-potable water to enter the system from a cross connection or other source. Backflow can also occur when an outside source is pressurized by air or gas, creating a higher pressure in the outside source than in the distribution system. From 1971 through 1998,

> "… chemical and microbial contamination from cross-connections and backsiphonage were responsible for most distribution system outbreaks. Outbreaks could be traced to backflow prevention devices that were needed but not installed, had been inappropriately installed, or had been inadequately maintained (Craun and Calderon, 2001)."

For example, in July 1997, 123 persons who had visited a New Mexico country club became ill with gastroenteritis. *E. coli* O86:H11 was isolated from 11 ill individuals and *Giardia* was isolated from one ill individual (Barwick et al., 2000). A heavy rainstorm caused a power outage at the country club two weeks before the gastroenteritis outbreak. It is believed that during the power outage, contaminated water may have siphoned back into the country club's water system due to low pressures. No backflow prevention device was present (Craun and Calderon, 2001).

Pressure transients can also create hydraulic disturbances that allow biofilm material on pipe surfaces or sediments to enter the bulk water. This phenomenon was observed during a major fire in a Texas city (Geldreich, 1996). The water demand for fire fighting resulted in reduced pressure in the water line. After the fire hydrant valve was closed and normal pressures were being restored in the water line, a significant water hammer was created in the pipe. Biofilm shearing occurred that released 125 to 200 *Pseudomonas aeruginosa* per milliliter to the finished water over a 24-hour period before subsiding to non-detectable levels.

4.3.2 Operations

If the distribution system is fed by multiple sources with varying water quality, the release of biofilms, scales, or sediments may occur at the interface between the sources. The City of Tulsa, Oklahoma, derives its water from two major surface water supplies that are located at opposite ends of the distribution system, creating three water quality zones: one for each plant and one at the interface zone in the distribution system where water from each plant mixes. For two years, the majority of positive coliform samples have occurred at the interface between the two treated waters in the distribution system (Kirmeyer et al., 2000). Although coliform data appeared to be linked to the interface area, the city was uncertain of the cause. Red or brownish water complaints were occurring at the interface, but subsided when the city held the production ratio near constant at each facility. The fluctuations in production likely caused loosening or dissolution of scale material due to changing water quality in the interface zone. Water quality changes consisted primarily of an increase in conductivity that may have resulted from low-flow conditions within the interface zone.

4.3.3 Maintenance Practices

Water main flushing and cleaning are routine maintenance practices often conducted within the distribution system. Line cleaning methods include air and water scouring, swabbing, pigging, and chemical and mechanical cleaning. Flushing and line cleaning practices can affect the distribution system water quality in a negative manner if not conducted properly. Improper flushing can result in moving a contaminant further into the distribution system.

Loose deposits are susceptible to entrainment and suspension under normal hydraulic scenarios, such as flow reversals and velocity changes (Friedman et al., 2003). Sudden flow increases (USEPA, 1992) or hydraulic disturbances (Characklis, 1988) can cause accumulated biofilm, scales, sediment, or tubercles to shear or slough, resulting in release to the water column. These disturbances can occur due to many factors, including flushing operations.

Flushing and disinfection following water main repair may not be sufficient to remove sources of contamination. Besner et al. (2004) investigated total coliform occurrence associated with water main repair sites. After repairs were complete, coliform were detected in flushed water samples and house samples collected near three repair sites. The authors hypothesized that increased water velocity in the main during flushing led to biofilm sloughing or sediment resuspension that contained coliforms. LeChevallier (1999) noted that the flushing velocity used in a repaired main is often too low to remove contaminants. Gauthier et al. (2001)

illustrated how coliform bacteria counts at the "B Street" sampling point in the Montreal distribution system increased after it was flushed, drawing water from the 14-inch main.

Besner et al. (2002a) identified distribution system work, including pipe flushing, valve operations, hydrant operations and low distribution system pressures, as highly probable causes of 15 positive total coliform samples in the Laval, Quebec system. Seven samples were collected from two sampling points in the same pressure zones where unidirectional flushing was performed during the same time period. Five samples collected from three sampling points were linked to localized low distribution system pressures that were related to construction work. Two samples were collected from a sampling point near the construction work after three valves were operated, causing flow reversals and low pressure conditions. One sample was linked to nearby hydrant operations that may have caused hydraulic disturbances such as sediment resuspension.

Mechanical cleaning and relining of pipes, as well as new main installation were identified as possible causes of a total coliform occurrence in the Moncton, New Brunswick distribution system (Besner et al., 2003). The authors used customer complaint calls and turbidity data for distribution system samples to establish approximate dates for distribution system maintenance work since maintenance records were not available. A positive coliform sample was obtained in the vicinity of this work during the same time period.

Incomplete curing of new paint and residual solvents leaching from the paint caused biological growth on interior surfaces of two finished water standpipes at Lakehaven Utility District (Kirmeyer et al., 2000). Visual inspection of the tank interiors revealed an extreme microbial growth and slimy surfaces. During the fall of 1989, these tanks had been cleaned, painted, and disinfected prior to returning to service. During the first eight months following the painting, only one incident of coliform bacteria was detected from tank water samples, but HPC levels began to show an increase. Customer complaints of a strange musty and fishy odor in their water also began to occur during this time period. On five occasions, the tanks were taken off-line and shock-chlorinated only to have a substantial increase in heterotrophic bacteria return within a short period. Historically, samples collected from these tanks produced HPCs levels in the range of 1 to 50 colony forming units (CFU)/mL. During the eight-month time period, samples from the tanks produced HPC levels in the range of 0 CFU/mL (after shock-chlorination) to 4,300 CFU/mL within about a four-week period.

4.3.4 Retention Time

Long retention time in the distribution system can reduce the water's disinfectant residual and allows the deposition and accumulation of sediment. Stagnant water can occur in dead-end pipes, fire protection storage tanks or finished water storage facilities that are over-sized or have periods of limited use. Stagnant water provides an opportunity for suspended particulates to settle into pipe sediments, for biofilm to develop, and for biologically mediated corrosion to accelerate (Brandt et al., 2004). An EPA Distribution System White Paper discusses (http://www.epa.gov/safewater/tcr/pdf/waterage.pdf) the effects of water age on distribution system water quality.

Gauthier et al. (2001) identified a possible cause of a total coliform occurrence in a distribution system with a retention time issue. The authors studied total coliform occurrences in a portion of the Montreal, Quebec, Canada distribution system to evaluate possible causes. For the 1997 to 2000 period, total coliform occurrence at one sampling point was thought to be initially caused by closure of a valve between two pressure zones that created dead-end conditions near the sampling point. After the valve closure, the water's chlorine residual dropped immediately to zero and total coliforms were detected one month later.

4.3.5 Presence of Nutrients

Some materials or system operations can introduce nutrients to the distribution system that may support growth of total coliform bacteria. For instance, if proper lubricants are not used in pumps, microbial growth may be supported. Also, some treatment operations (e.g., ozonation, chlorination) may lead to the production of available nutrients that may support growth. The effects of nutrients are described in more detail in the EPA paper on biofilms (USEPA, 2002). and on treatment and nutrients (USEPA, 2006).

5. Summary

The purpose of this paper is to review existing literature, research, and information on public water supply distribution system occurrences of total coliform bacteria and the circumstances and deficiencies identified as having caused those events. Total coliform bacteria may be present in the distribution system if three conditions simultaneously occur: a source of total coliform bacteria; a pathway into the distribution system; and a mechanism that allows the bacteria to be carried on this pathway into the distribution system or that allows bacteria within biofilms, corrosion tubercles or sediment to enter the water.

Sources of total coliform bacteria include the following:

- Soil and Water Surrounding Pipes
- Biofilms and Microbial Growth
- Corrosion Tubercles
- Weather-Related Events
- Customer Connections
- Materials Added to the Distribution System
- Sediments

Pathways through which total coliform bacteria can enter the distribution system include the following:

- Finished Water Storage Facilities
- Cross Connections and Backflow
- Intrusion and Main Breaks
- Treatment Breakthrough

Mechanisms that allow coliform bacteria to enter the distribution system (assuming a source of contaminants and a pathway are present) or that allow bacteria to proliferate in the distribution system include the following:

- Hydraulic Conditions
- Operations
- Maintenance Practices
- Retention Times
- Presence of Nutrients

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